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This program has been aimed at the technology development of near field optical imaging in reflection, transmission and emissive modes using radiation from UV to IR. In this contract period, we have designed and constructed an optical near field/shear force microscope capable of 30 nm resolution. This instrument has been used to demonstrate the difference between topographic and materials contrast and enabled us to quantitatively evaluate the character of near field images. We have shown the role that polarization and detector geometry play in reflection near field imaging and quantitatively assessed spatial resolution in near field systems. In addition, we have demonstrated near field imaging of 1.3μm wavelength radiation and near field printing of UV radiation at close to $\lambda/10$ resolution.

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# FINAL REPORT
# AFOSR 91-0219

# NEAR FIELD LIGHTBEAM TECHNOLOGY

2/15/91 - 12/14/94

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## Table of Contents

# I. ABSTRACT

This program has been aimed at the technology development of near field optical imaging in reflection, transmission and emissive modes using radiation from UV to IR. In this contract period, we have designed and constructed an optical near field/shear force microscope capable of 30 nm resolution. This instrument has been used to demonstrate the difference between topographic and materials contrast and enabled us to quantitatively evaluate the character of near field images. We have shown the role that polarization and detector geometry play in reflection near field imaging and quantitatively assessed spatial resolution in near field systems. In addition, we have demonstrated near field imaging of 1.3μm wavelength radiation and near field printing of UV radiation at close to λ/10 resolution.

# II. PROGRESS REPORT

## A. Review of Near Field Optical Technology

The field of near field optics pioneered in this laboratory has exploded in the past several years. The 1st International Conference on Near Field Optics was held in the fall of 1992 and the 2nd International Conference was in October, 1993, in Raleigh, North Carolina. There were 150 people from 12 separate countries attending the 1993 meeting. From papers presented, 36 were put into manuscript form and published as a separate volume of Ultramicroscopy of which I was the editor (1). In addition, my laboratory at Cornell has been involved in discussion with several other laboratories throughout the country interested in setting up efforts in near field technology. Although our program is of modest size, we have been able to have considerable impact on the burgeoning field of near field imaging.

## B. Comparative Near Field Measurements

We have continued to develop the technology for near field tip probes. From initially using hollow capillary tubes, we now use single mode optical fiber probes with tip ends close to 30 nm in diameter. Such probes allow for signal throughput many orders of magnitude greater than can be achieved with hollow capillary tubes. And calculations indicate that effective resolution in the range of 10-15 nm may be achievable using this type of probe structure. Calculations have also been made of the fiber pulling process to optimize and control the shape of the nano-scale end of the fiber since the shape effects the ultimate signal throughput attainable.

For the 1st time we have been able to directly measure the near field radiation profile of radiation emanating from these pointed fibers and pointed capillary tube tips. These profiles are determined by scanning a metalized probe tip over a small microfabricated aluminum "dot" or "line" whose lateral dimension is smaller than the probe tip diameter. The aluminum structures are on quartz substrates and the signal is detected in transmission. To the extend that such objects can be considered "point" or "line" objects, the resulting measurements yield the point spread function of the near field scanning optical microscope (NSOM) instrument. Results of these measurements were published in reference 2. We have shown that to a very good approximation, the near field probe shape can be treated as a simple

Gaussian whose width is related to the effective diameter of the probe tip end. Using this information, we have developed a simple formalism for treating near field imaging in the context of Fourier optics and hope to use this as the foundation toward developing a simple image simulation model -- the first step towards quantitative microscopy.

C. Diagnostics at 1.3mm Wavelength

The new near field microscope system built under this contract (and described later) has been used to measure the near field radiation patterns from the facet end of lasers and fiber optic couples from a TOSA interconnect device from IBM Endicott (Optoelectronic Enterprise). We have made these measurements at 1.3m wavelength in an attempt to understand coupling efficiency in these interconnects. In addition, we have also used the high spatial resolution of the near field fiber probe detector to obtain a very high resolution intensity map near the focal plane of GRIN lens coupled to a semiconductor laser. The high resolution NSOM type images allowed us to view "defects" in the intensity radiation pattern which could not be resolved using conventional "optics". The other point to note here is that our standard phototube detector optimized for blue light, has still sufficient quantum efficiency (although down by 3 orders of magnitude) at 1.3m to allow relatively noise free measurements. These measurements were not continued after IBM sold their optoelectronic business to LORAL.

D. Near Field Optical Lithography

Although we had initially proposed to evaluate near field lithography using the scanned probe method, we opted to first look at the possibilities of parallel "conformal" printing since that offered the potential of higher throughput. A Master of Engineering student (J. Zola) on leave from the Advanced Technology Center at IBM, East Fishkill developed a series of optical masks using direct near field "contact" printing. Although only preliminary, he was able to demonstrate sub 100 nm featured size lithography using thin layer resist technology. The results of some of his efforts are shown in figure 1. This figure shows scanning electron micrographs of patterns etched into silicon dioxide after being exposed in the near field to 405 nm radiation. The $SiO_2$ has been grown on a Si substrate. A pattern definition close to 80 nm resolution has been achieved using a resist thickness of approximately 80 nm. If we can produce (reliably) 40 nm thick resists and use a tri-layer process, optical printing at 50 nm resolution should be achievable.

E. Compact Optical Near Field/Shear Force Microscope with Variable Geometry Detectors

A portion of the work during this contract has concentrated on finishing the construction and testing of a new modular near field microscope and printing system. The system is shown in schematic in figure 2 and an image of it is shown in figure 3. It utilizes shear-force (on the optical fiber tip) as the feedback mechanism to get accurate control of the tip to sample distance (better than 1 nm) and can be used in reflection, transmission or emissive mode imaging. One should keep in mind

that due to budget constraints, we have built the entire system from scratch including the electronics and computer interface.

The use of shear force microscopy signals for the fiber probe feedback gives good reliability and allows for a convenient non-optical topographic feedback. The shear force signal is generated by dithering the fiber probe tip in a direction parallel to the sample surface. The change in dithered amplitude as the tip gets closer to the surface gives us the "height" feedback signal thus allowing one to collect the near field optical signal at constant height. The advantage of this "frictional force" signal rather than the standard vertical dithered atomic force signal is reliability -- i.e., the probe doesn't have to be positioned as close to the sample. This last aspect may have considerable benefit in using near field imaging for optical metrology.

F. Image Understanding

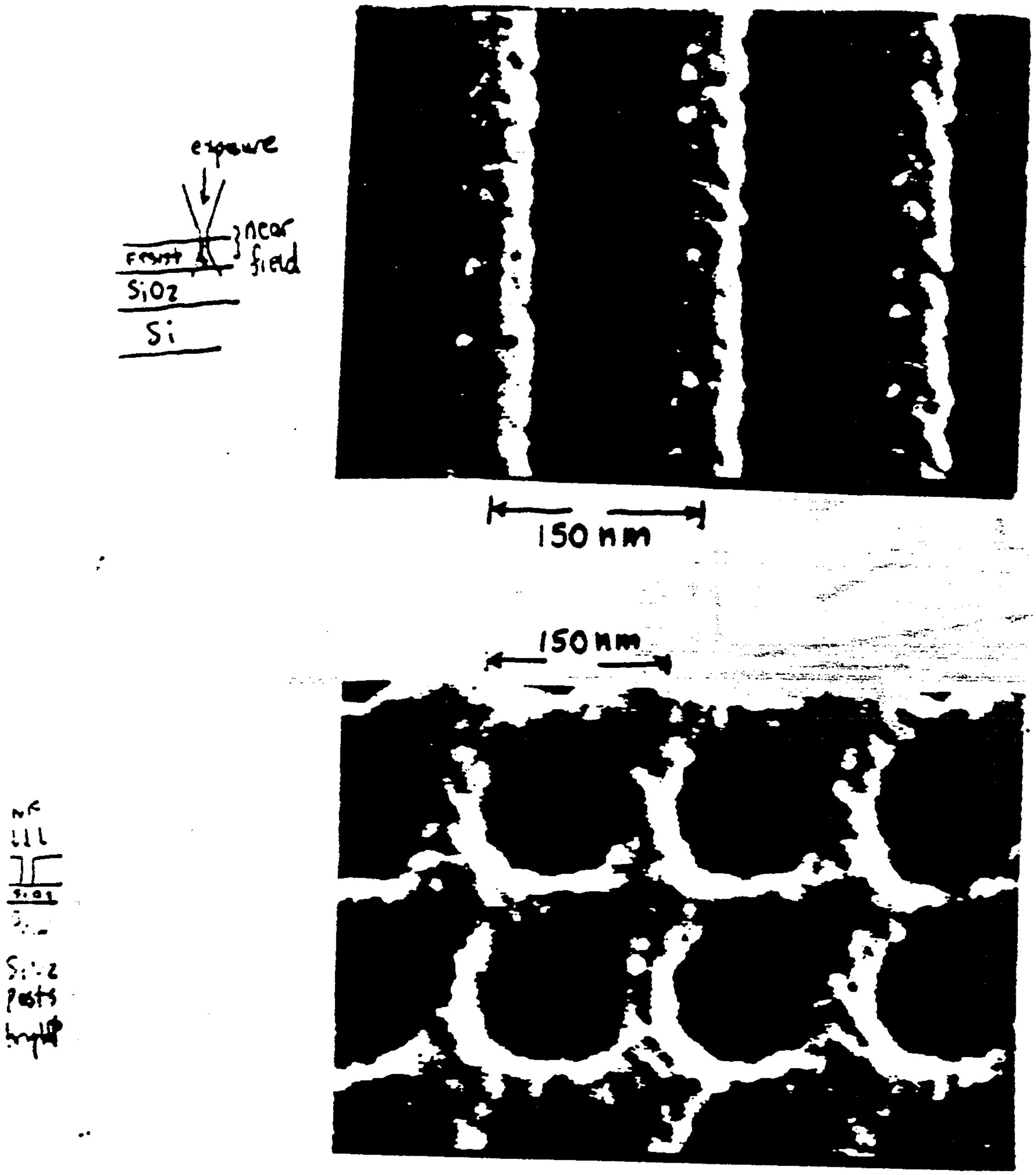
One of the breakthroughs we have achieved during this period is based upon my experience with the scanning electron microscope. The three dimensional like images one generally obtains come about by using an off-axis secondary electron detector. A first order interpretation of the image can be obtained by looking at the sample as if it had been illuminated from the direction of the detector and viewed from the direction of the incident electron beam. In the NSOM case, we position the reflecting objective off-axis at an angle of ~30-45° from the sample surface. We then get a "shadowed" image in which parts of the sample away from the reflecting objective used to collect the light are shadowed (see figure 4). While the images are more complicated than this, it allows for an easy zeroth order interpretation. Note in the images that in certain instances the near field reflection image is of higher resolution than the shear force image -- and in some instances "appears" to give better resolution than would be expected based upon the probe tip diameter alone (3).

We now have a more complete understanding of the shadowed nature of the reflection near field image obtained using an asymmetrical detection system. And we have a much better knowledge of how the topographic nature of the near field image comes about. In our Applied Optics paper (a preprint is included, ref. 4) we explain the phenomenon. For homogenous materials, this is a first step towards utilizing near field microscopy as a metrology tool (see figure 5). We have been contracted by Mitutoyo, Inc. to have one of their engineers from Japan spend a year in my lab to learn the technology, but have not allowed their request.

In addition to obtaining a better understanding of the topographical content in a reflection NSOM image, we have also explored the polarization content of the image with the goal of being better able to understand what the materials contrast images mean and with an eye towards imaging of magnetic materials. The effect of detection geometry relative to the incident plane of polarization of light coming from optical and magnetic materials and we will begin to explore this possibility. In addition, our polarization studies have shown that one still must be cautious in interpretations of NSOM images.

G. Summary of Accomplishments (2/15/91 - 12/14/94)

- Demonstrated quantitative measurements of MTF for near field imaging
- 1st demonstration of near field imaging at 1.3mm wavelength
- Demonstration of near field printing at 50 nm resolution
- Design and construction of compact near-field/shear force microscope with variable detector geometry
- 1st demonstration of simultaneous transmission and reflection near field images
- 1st direct 3D topographical near field optical imaging at resolutions better than simultaneous shear force imaging
- Evaluation and demonstration of topographic material and polarization contrast in near field optical imaging
- Edited 1st complete peer- reviewed volume of Near Field Optics in Ultramicroscopy




etched into $SiO_2$ on Si ...

Figure 1: SEM micrographs of patterns lithographically defined using near field optical printing. The resist was exposed in the near field and developed positively. The structures in the $SiO_2$ were produced by RIE through the exposed resist areas. Line widths are less than 80 nm.

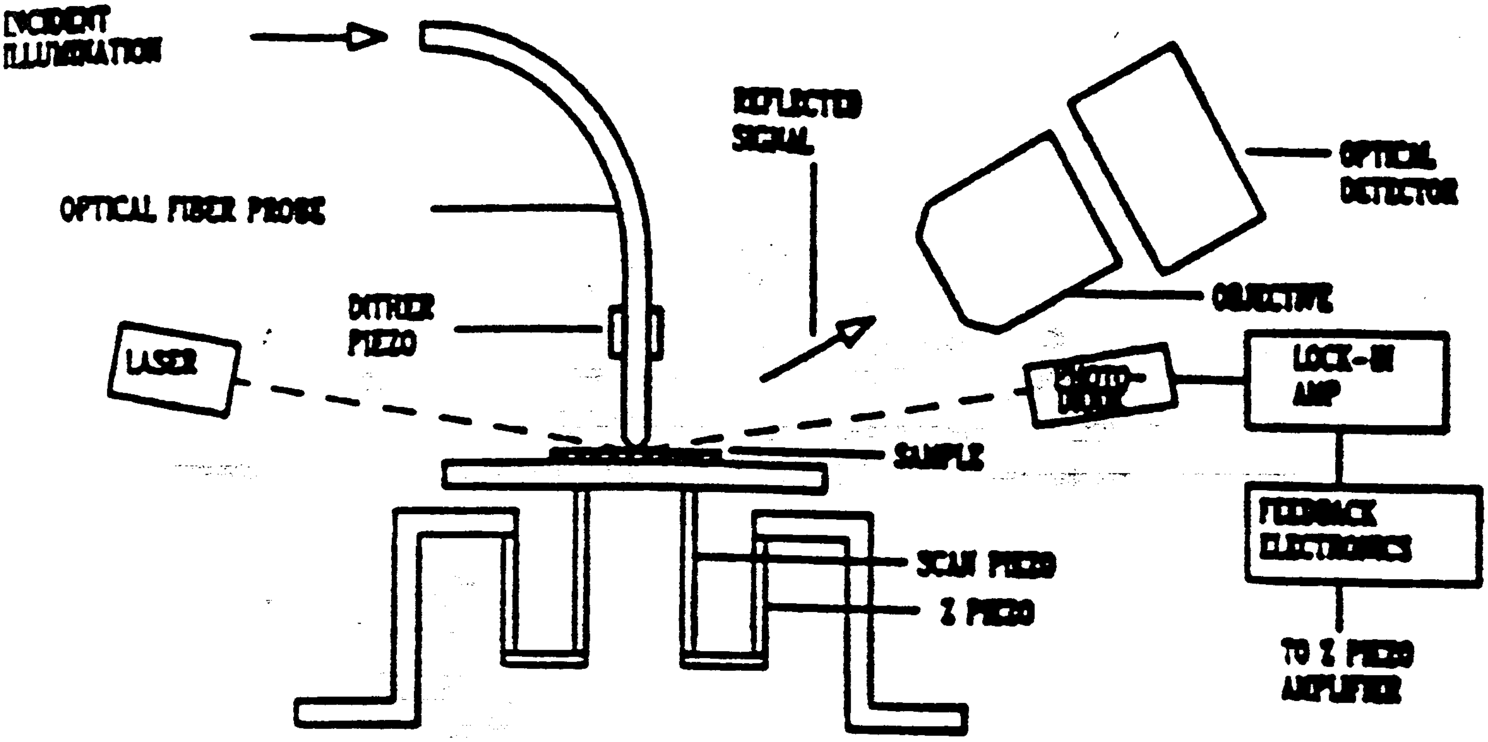



Figure 2: Schematic of a compact reflection near field microscope with laser detected shear force feedback.

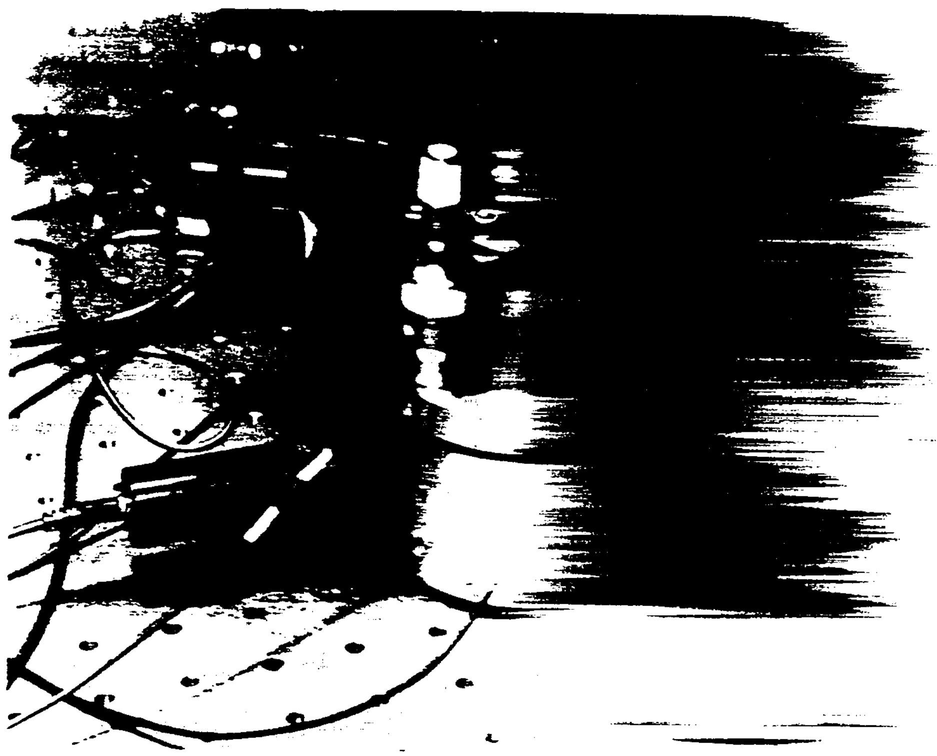


Figure 3: Picture of the reflection near field

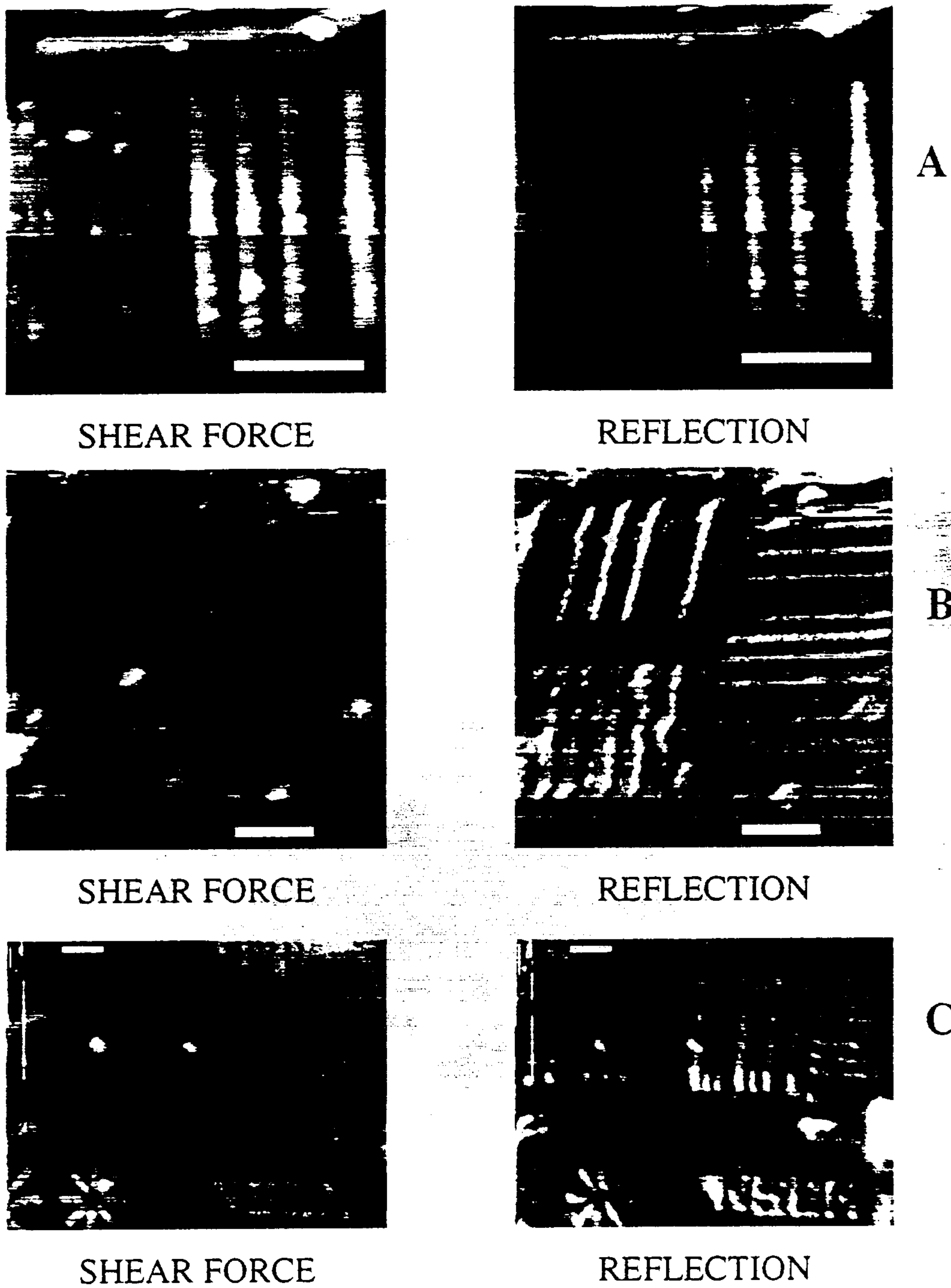
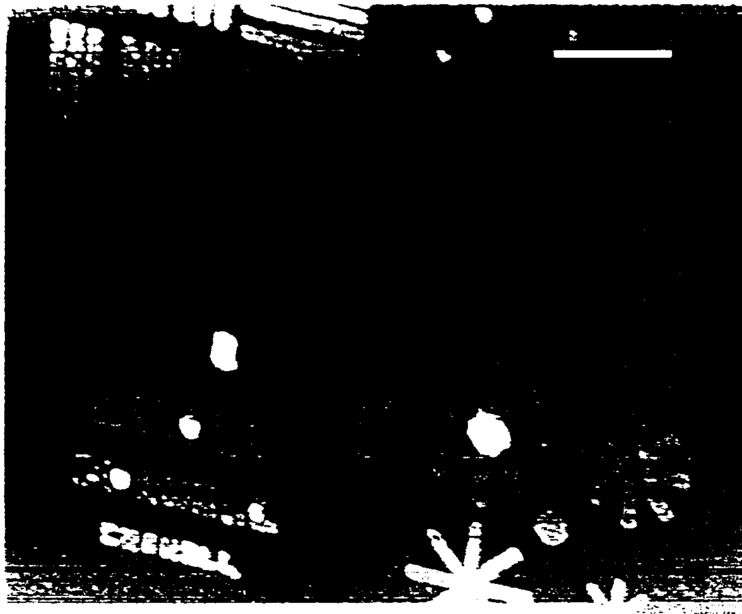
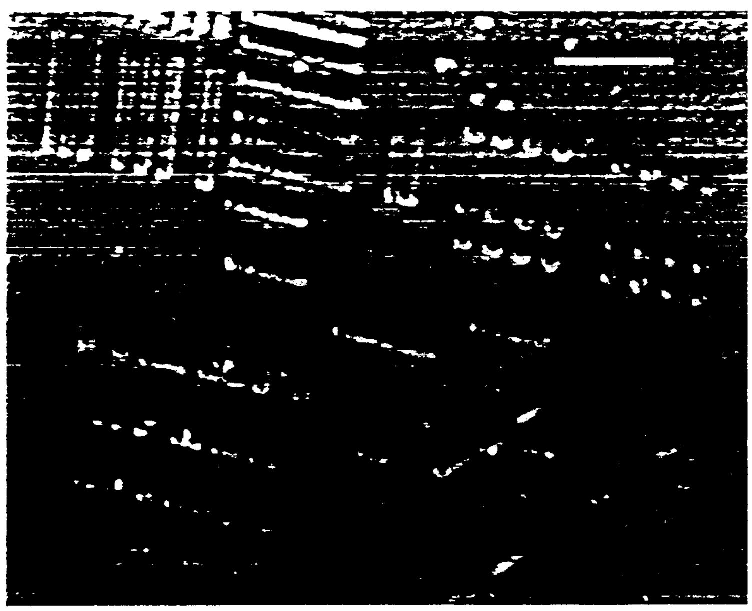



Figure 4: Images of aluminum bars on silicon taken using the near field microscope of figure 3. The left image is the shear force image, the right is the simultaneously taken near field optical image. The scale bar is 0.9mm.



SHEAR FORCE



REFLECTION

Figure 5: Comparison of simultaneously obtained shear force and reflection near field images of an aluminum pattern on aluminum. The shadowing is a direct result of sample topography. No image processing was performed. The marker is .9mm.

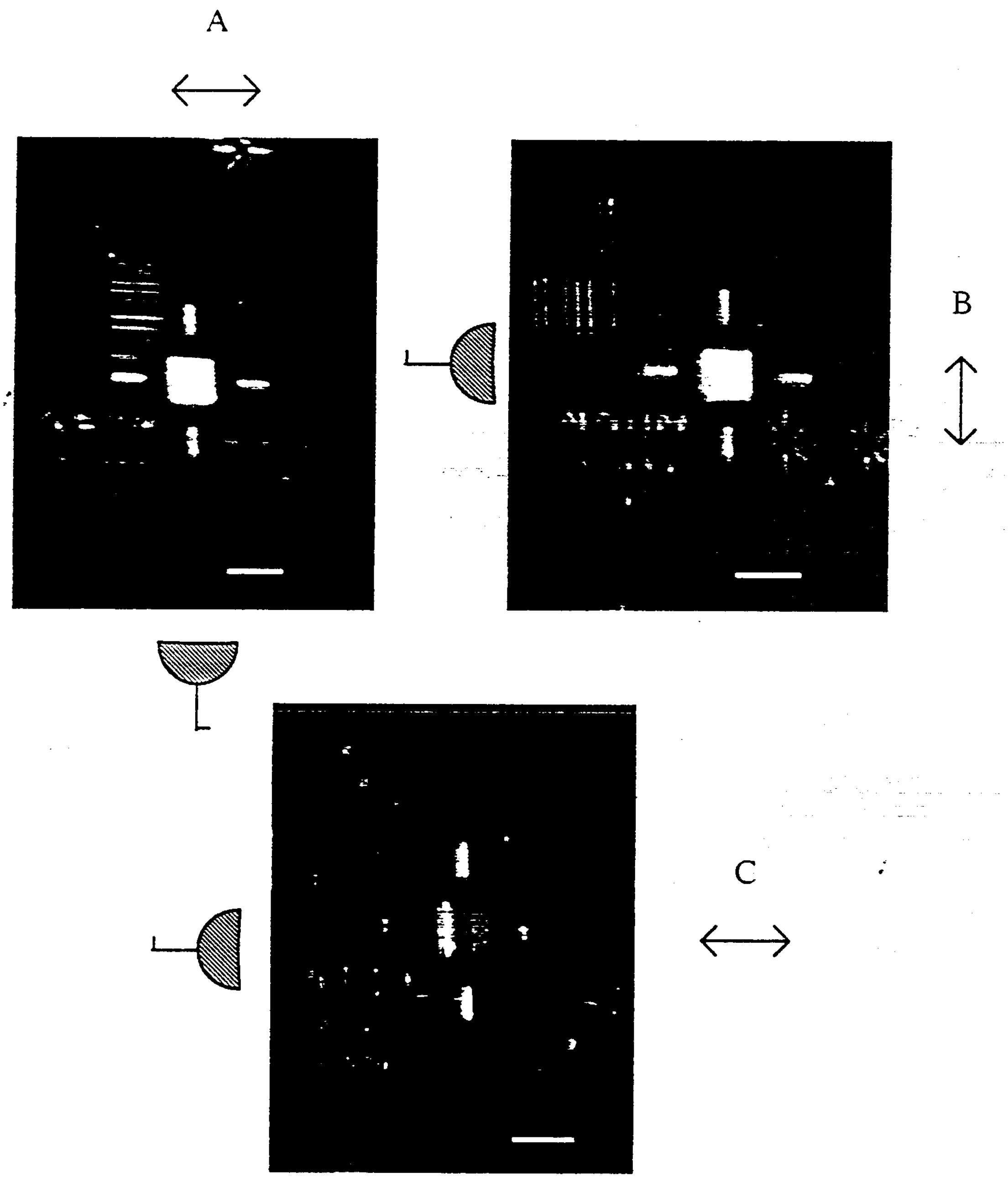



Figure 6: Reflection near field images of an aluminum test pattern on glass. All images taken with the same probe under varied probe and detector orientations.

III. APPENDIX

A. Principal Investigator Information Data

Articles Published Relevant to Grant

1. M. Isaacson, J. Cline and H. Barshatzky, "Near Field Optical Microscopy" in Scanned Probe Microscopies: An AIP Symposium, (eds. K. Wickrahmasinge and A. MacDonald, AIP Press, 1991).

2. J. Cline, H. Barshatzky and M. Isaacson, "Scanned-Tip Reflection-Mode Near-Field Scanning Optical Microscopy", Ultramicroscopy 38, 299-304 (1991).

3. M. Isaacson, J. Cline and H. Barshatzky, "Near-Field Scanning Optical Imaging II", J. Vac. Sci. Technol. B9(6), 3103-3107 (Nov/Dec. 1991) (Invited).

4. M. Isaacson, J. Cline and H. Barshatzky, "Resolution in Near Field Optical Microscopy", Ultramicroscopy 47, 15-22 (1992) (Invited).

5. J. Cline, H. Barshatzky and M. Isaacson, "Resolution in Near Field Imaging", Proc. SPIE Vol. 1639, 2-12 (1992) (Invited).

6. J.A. Cline and M. Isaacson, "Probe-Sample Interactions in Reflection Near Field Scanning Optical Microscopy", Applied Optics (in press)

7. J. Cline and M. Isaacson, "Comparison of Different Modes of Reflection in Near-Field Optical Imaging", Ultramicroscopy, 57(2/3), 147-152 (1995).

8. M. Isaacson, ed. "Near Field Optics", Ultramicroscopy 57(2/3), 1-322 (1995).

Invited Presentations Related to Work on this Grant

1. May 1991. QELS Meeting of the Optical Society of America, Baltimore, Maryland: "Beyond the Diffraction Limit: Optical Microscopy with 1/10 Resolution".

2. May 1991. 35th International Symp. on Electron, Ion & Photon Beams, Seattle, Washington: "Near Field Scanning Optical Microscopy II".

3. July 1991. LEOS Meeting of the IEEE, Newport Beach, California: "Novel Nanofabrication Methods for Studies in Optical and Mesoscopic Physics".

4. August 1991. Electron Microscopy Society of America Annual Meeting, San Jose, California: "Revolution in Near Field Optical Imaging".

5. September 1991. 18th National Congress of the Italian Microscopical Society: "Scanning Near Field Optical Microscopy".

6. January 1992. Gordon Conference on Non-Destructive Analysis, Oxnard, California: "Near Field Optical Imaging".

7. January 1992. 2nd International OIDTA Forum, Workshop on "New Optical Microscopies", Okinawa, Japan: "Near Field Optical Microscopy: Problems and Potentials".

8. January 1992. Scanning Optical Microscopy Post-Conference Meeting; Tokyo Japan: "Near Field Imaging; Why Has it Taken a Half Century?"

9. January 1992. SPIE Conference on Scanned Probe Microscopies, Los Angeles, California: "Resolution in Near Field Microscopy".

10. February 1992. American Association for the Advancement of Science, Symposium on Microscopy, Chicago, Illinois: "Near Field Microscopy: Beating the Diffraction Limit".

11. May 1992. Optical Society of America, Regional Meeting on New Imaging Methods, Rochester, New York: "Near Field Optical Microscopy".

12. July 1992. American Association for the Advancement of Science, Science Innovations '92, San Francisco, California: "Optical Microscopy Without Lenses".

13. September 1992. 11th Annual Symposium on Advances in Microscopy, Duke University Medical Center, Pine Knoll Shores, North Carolina: "Optical Microscopy Without Lenses: An Example of An Idea Before Its Time".

14. December 1992. Symposium of the Abteilung Elektronenmikroskopie, Fritz Haber Institute, Berlin: "Near Field Optical Imaging".

15. March 1993. Spring Meeting of the Microscopy Society of the Ohio River Valley, Louisville, Kentucky: "Microscopy Without Lenses".

16. March 1993. American Physical Society, Seattle, Washington: "Near Field Optical Imaging".

17. April 1993. General Electric Symposium on Advances in Microscopy, Schenectady, New York: "The Revolution in Microscopy".

18. May 1993. Southeastern Electron Microscopy Society, Birmingham, Alabama: "300 Years After Hooke and van Leeuwenhoek: Microscopy Without Lenses".

19. October 1993. Iowa Microscopy Society, University of Iowa, Iowa City, Iowa: "Beating the Difrraction Limit: Microscopy Without Lenses".

20. October 1993. Syracuse Microscopy Symposium, SUNY Syracuse Health Sciences Center, Syracuse, New York: "Optical Microscopy Without Lenses".

21. October 1993. Louisiana Society of Electron Microscopy, Tulane University, New Orleans, Louisiana: "300 Years After Hooke and van Leeuwenhoek: Microscopy Without Lenses".

22. October 1993. Second International Conference on Near Field Optics, Raleigh, North Carolina: "Reflection Near Field Imaging".

23. October 1993. Great Lakes Electron Microscopy Affiliates Meeting, Indianapolis, Indiana: "300 Years After Hooke and van Leeuwenhoek: Microscopy Without Lenses".

24. December 1993: Shell Development Corporation, Houston, Texas: "Microscopy Without Lenses".

25. March 1994. American Physical Society Meeting, Symposium on Microscopy, Pittsburgh, Pennsylvania: "Optical Microscopy Without Lenses".

26. April 1994. Northern California Microscopy Society, Syntek Corporation, Palo Alto, California: "300 Years after Hooke and Van Leeuwenhoek: Microscopy Without Lenses".

27. April 1994. University of Minnesota, Dept. of Chemical Engineering and Materials Science. Microscopy Symposium, "Microscopy Without Lenses".

28. June 1994. Congressional Biomedical Caucus on Instrumentation, Rayburn Building, Washington, D.C., "The Revolution in Scanning Microscopies".

29. July 1994. 13th International Congress on Electron Microscopy, Paris, France: "300 Years After Hooke and Van Leeuwenhoek: Microscopy Without Lenses". (keynote address)

30. August 1994. 52nd Annual Meeting of the Microscopy Society of America; Presidential Symposium on Microscopy in the 21st Century, New Orleans, Louisiana: "The Revolution in Optical Microscopy".

<u>Graduate Students On This Project</u>

Harry Barshatzky - MS, Applied Physics (rec'd 1992)
Jerrold Cline - Ph.D., Applied Physics (rec'd 1994)
Jeffrey Zola - MEng, Engineering Physics (rec'd 1992)
Felix Anderson - MEng, Engineering Physics (rec'd 1994)
Craig Gemmill - Ph.D. Candidate, Applied Physics

Undergraduate Students On This Project

Jill Berger, BS - Engineering Physics (rec'd 1992)
Konrad Lehnert - BS, Physics (Harvey Mudd College) (rec'd 1992)
Lynn Gabbay - BS, Engineering Physics (rec'd 1993)
Paul Williams - BS, Physics (Alabama A&M) (rec'd 1993)
William Griffith - BS, Electrical Engineering (Dartmouth) (rec'd 1994)

Professional Honors, Accomplishments During This Period

Alexander Von Humboldt Senior Scientist Award, 1992
Elected President of the Microscopy Society of America, 1993
Member, Council of Scientific Society Presidents, 1991-1994
Elected Fellow of American Association for the Advancement of Science, 1993